

Patent Application

of

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for

10 **Apparatus and Method for Optical Characterization of a Sample  
Over a Broadband of Wavelengths While Minimizing Polarization**

**Changes**

**CROSS-REFERENCE TO RELATED APPLICATIONS**

15 The present application is co-filed with application "Apparatus and Method for Optical Characterization of a Sample Over a Broadband of Wavelengths With a Small Spot Size" by Ray Hebert, Marc Aho and Abdul Rahim Forouhi, which is herein incorporated by reference.

### **FIELD OF THE INVENTION**

The present invention relates generally to an apparatus and method for optically characterizing the properties of a sample on reflection and transmission of light over a broadband of 5 wavelengths while minimizing polarization changes.

### **BACKGROUND OF THE INVENTION**

Advances in microelectronics necessitate components with ever smaller critical dimensions. Manufacturing such components 10 requires the use of shorter wavelengths of light in the lithography processes employed in component fabrication. This, in turn, has lead to a need to measure the optical characteristics of samples such as, among other, photolithographic masks and fabricated components over a broad 15 range or broadband of wavelengths including the UV. Typically, in these measurements the cross-sectional diameter of a beam of light focused on the sample is large enough to spatially average the optical characteristic being measured yet small enough to resolve spatial variations across the sample. As the critical 20 dimensions have decreased so too has the required diameter of the beam of light on the sample. It is now desirable to have a diameter of less than 100 micron.

As with many engineering problems, the design of an optical 25 system to measure the optical characteristics of such a sample represents a tradeoff. For example, when illuminating the beam of light with the broadband of wavelengths from a light source onto a surface of the sample, it is desirable to have a small spot size but not a diffraction limited spot. In addition, this should be accomplished in an optically efficient manner. There

is, therefore, a tradeoff in this regard between a need for optical components with a low f-number (for higher optical efficiency) and a need for optical components with a high f-number (for a small spot size over a practical depth of field with minimal aberration and angles of incidence) and thus a small cone of rays corresponding to the beam of light that is used in the optical system, i.e., the useful light. Similar design tradeoffs occur in the collection and illumination on a detector of the beam of light reflected from the sample and the beam of light transmitted through the sample.

The need to operate over the broadband of wavelengths is a further design constraint for with many optical components because they are subject to a variety of effects such as chromatic aberration and absorption. For refractive optical components these effects become pronounced as the wavelengths approach the UV. There exist optical systems based on refractive optical components in the prior art that operate over a broadband of wavelengths with a small diameter of the beam of light on the sample. In these systems, attempts are made to compensate for chromatic aberration and absorption effects. However, this adds expense and complexity to these optical systems.

Reflective optical components are a suitable solution to this technical challenge. A wide variety of components are available including mirrors with non-spherical shape, such as an off-axis paraboloid shape, henceforth called an off-axis parabolic mirror. However, non-spherical shaped mirrors can add expense to the optical system, especially when such mirrors are manufactured by diamond turning. Optical systems including

toroidal, spherical and elliptical mirrors are disclosed in the prior art. For examples, see US 5,910,842, US 6,583,877 and US 6,128,085.

5 In addition, many prior art broadband optical systems combine refractive and reflective optical components. However, such catadioptric systems do not avoid the complexity and expense needed to overcome the chromatic aberration and absorption issues associated with refractive optical components.

10 Furthermore, when different samples are characterized, the beam of light in the optical system will need to be focused on the sample to correct for effects such as varying surface topography. Such an adjustment is problematic if the adjustment of the position of certain optical components in the optical system necessitates the adjustment of the position of many other optical components, since this can easily lead to misalignment.

15 A preferred solution would allow the beam of light to be focused on the sample by adjusting a minimum number of components in the optical system or a simple assembly of components. Furthermore, such a preferred solution would be a sufficiently compact and simple optical system that a single light source could be used to optically characterize the reflection and transmission properties of the sample.

20 Addition information in the optical characterization of the sample can be obtained by selectively polarizing the beam of light illuminating the sample, analyzing the polarization of the beam of light reflected off of or transmitted through the sample, or both. This poses yet another technical challenge, since it is known that the polarization of the beam of light is changed on reflection from or transmission through materials.

It would be beneficial if such polarization changes associated with the optical components and the sample substrate could be minimized.

There is a continued need, therefore, for a compact optical system for optical characterization of a sample, which operates over a broadband of wavelengths with a small diameter of the beam of light on the sample and which employs reflective optics with a minimum number of optical components such that advantageous components such as off-axis parabolic mirrors can be used. There is also a need for such an optical system that can be focused by adjusting the position of the minimum number of optical components or a simple assembly of components, and for an optical system that minimizes changes in the polarization of the beam of light.

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#### **OBJECTS AND ADVANTAGES**

In view of the above, it is a primary object of the present invention to provide an apparatus and method that enables optical characterization of the properties of a sample on reflection and transmission of a beam of light over a broadband of wavelengths with a small spot size on the surface of the sample while minimizing changes in the polarization of the light. More specifically, it is an object of the present invention to provide a broadband apparatus with a small spot size on the surface of the sample, and a method of using this apparatus, for optical characterization of the properties of the sample on reflection and transmission of the beam of light through the use of optical light paths comprising reflective optical components, including off-axis parabolic mirrors, which

minimize changes in the polarization of the beam of light. It is a further object of the present invention to provide an apparatus, and a method of using this apparatus, where the spot size on the surface of the sample can be brought into focus 5 without extensive adjustment of the position of these optical light paths.

These and numerous other objects and advantages of the present invention will become apparent upon reading the following description.

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#### **SUMMARY**

The objects and advantages of the present invention are secured by an apparatus and method for the optical characterization of the properties of a sample on reflection and transmission of a beam of light, with a small spot size on the sample, over a broadband of wavelengths. A broadband beam of light from a light source is fractionally magnified and illuminated onto a top surface of the sample. A portion of the broadband beam of light is reflected from the top surface of the sample, a portion 15 of the broadband beam of light is transmitted through the sample and a portion of the broadband beam of light is absorbed. The portion of the broadband beam of light reflected from the top surface of the sample is redirected and illuminated onto a first detector. The portion of the broadband beam of light transmitted through the sample is redirected from a bottom 20 surface of the sample and illuminated onto a second detector. These functions are accomplished using an illumination optical light path, a reflection optical light path and a transmission optical light path, each of which comprises reflective optical 25

components, thereby eliminating chromatic aberrations from these components. Pairs of planar and off-axis parabolic mirrors are used to redirect and magnify the broadband beam of light. In a preferred embodiment, the planar and off-axis parabolic mirrors are coated with a UV-enhancing aluminum coating. The broadband beam of light in the illumination optical light path, the reflection optical light path and the transmission optical light path is collimated between the pair of parabolic mirrors in each optical light path. This configuration allows focusing of the broadband beam of light on the top surface of the sample by adjusting a position of one of the pairs of planar and off-axis parabolic mirrors without requiring adjustment of the position of other components in each of the optical light paths.

In a preferred embodiment, polarization changes in the beam of light in the illumination optical light path, the reflection optical light path and the transmission optical light path are minimized by ensuring that angles of incidence and reflection of the broadband beam of light from the planar and off-axis parabolic mirrors in each of the light paths are small (near the normal to the mirrors) and that the angles in the beam of light illuminated on, reflected from or transmitted through the sample are near normal to the top surface or the bottom surface of the sample.

In another embodiment of this invention, an optical fiber is used to redirect the portion of the broadband beam of light transmitted through the sample to illuminate the second detector.

In another embodiment of this invention, a polarizing means is incorporated into at least one of the optical light paths to adjust the polarization of the broadband band beam of light.

5 In another embodiment of this invention, the portion of the broadband beam of light reflected from the sample and the portion of the broadband beam of light transmitted through the sample are each redirected and illuminated onto a common detector.

10 A detailed description of the invention and the preferred and alternative embodiments is presented below in reference to the attached drawing figures.

#### **BRIEF DESCRIPTION OF THE FIGURES**

15 Fig. 1 is a diagram illustrating an apparatus according to the invention.

Fig. 2 is a diagram illustrating another embodiment of an apparatus according to the invention.

Fig. 3 is a diagram illustrating a side view of one of the planar mirrors of the apparatus in Fig. 1 or Fig. 2.

20 Fig. 4 is a diagram illustrating a side view of one of the off-axis parabolic mirrors of the apparatus in Fig. 1 or Fig. 2.

Fig. 5 is a diagram illustrating the focusing of the broadband beam of light onto the sample surface.

25 Fig. 6 is a diagram illustrating a cross-sectional view of the broadband beam of light.

Fig. 7. is a diagram illustrating the beam of light incident, reflected and transmitted from a surface with the

10 polarization of the light perpendicular to the plane defined by the incident and reflected light.

5 Fig. 8 is a diagram illustrating the beam of light incident, reflected and transmitted from a surface with the polarization of the light in the plane defined by the incident and reflected light.

10 Fig. 9 shows the calculated amplitude coefficient as a function of the angle of incidence for light incident in air onto an aluminum object.

#### DETAILED DESCRIPTION OF THE EMBODIMENTS

15 A preferred embodiment of the invention is illustrated in Fig. 1. An apparatus 100 according to the invention comprises a first optical light path 110, a second optical light path 160 and a third optical light path 180. A light source 112 produces the broadband beam of light 114 between 190 nm and 1100 nm (broadband beam 114 is identified by its extremal rays in Fig. 1). An arc source, such as a Hamamatsu L2-2000 series deuterium lamp, is suitable for the UV portion of the spectrum, and a tungsten lamp for the visible and IR portions of the spectrum. A combination of the deuterium lamp and the tungsten lamp is suitable as the light source 112. The broadband beam of light 114 is redirected on reflection off of a first planar mirror 116. A model 01-MGF-005/028 planar mirror from Melles-Griot is suitable as the planar mirror 116.

20 Referring to Fig. 3, the broadband beam of light 114 has a maximum angle of incidence 120 relative to a normal 118 to the planar mirror 116 and a maximum angle of reflection 122 relative to the normal 118 of the planar mirror 116. By keeping the maximum angle of incidence 120 and the maximum angle of

reflection 122 small, that is, negligible with respect to the normal 118, changes in the polarization of the broadband beam of light 114 are minimized. The same technique is used for planar mirrors 138, 164, 170, 190 and 196 in the apparatus. This 5 technique is further described in Figs. 7-9.

Referring to Fig. 7, two regions, 300 and 302 are separated by a surface 304. There is incident light 312, with an angle of incidence 326 relative to a normal 306, reflected light 318, with an angle of reflection 328 relative to the normal 306, and 10 transmitted light 324, with an angle of transmission 330 relative to the normal 306. The electric field 308 in incident light 312, the electric field 314 in reflected light 318 and the electric field 320 in transmitted light 324 are directed perpendicular to the plane defined by the incident light 312 and the reflected light 318. The incident light 312 has a magnetic field 310, the reflected light 314 has a magnetic field 316 and the transmitted light 324 has a magnetic field 322. Referring 15 to Fig. 8, in an alternate polarization the electric field 332 in the incident light 312, the electric field 336 in the reflected light 318 and the electric field 340 in the transmitted light 324 are directed in the plane defined by the incident light 312 and the reflected light 318. The incident light 312 has a magnetic field 334, the reflected light 318 has a magnetic field 338 and the transmitted light 324 has a magnetic field 342. For this geometry, any electric field 20 polarization can be obtained by the linear superposition of the electric field polarizations shown in Figs. 7 and 8. Thus, it is sufficient to consider the impact of reflection and 25 transmission for these two polarizations.

Referring to Fig. 9, the calculated amplitude coefficients using Fresnel's equations for light, in a medium in region 300 with an index of refraction of 1.0, reflected off of and transmitted through aluminum in region 302, with an index of refraction of 1.39, as a function of the angle of incidence 326 is shown. The four amplitude coefficients are  $r_{\parallel\parallel}$ ,  $r_{\perp\perp}$ ,  $t_{\parallel\parallel}$  and  $t_{\perp\perp}$ , where  $r_{\parallel\parallel}$  and  $t_{\parallel\parallel}$  is the ratio of the parallel component of the electric field 336 in the reflected light 318 and the parallel component of the electric field 340 in the transmitted light 324 relative to the parallel component of the electric field 332 in the incident light 312, and  $r_{\perp\perp}$  and  $t_{\perp\perp}$  is the ratio of the perpendicular component of the electric field 314 in the reflected light 318 and the perpendicular component of the electric field 320 in the transmitted light 324 relative to the perpendicular component of the electric field 308 in the incident light 312. As shown in Fig. 9, the amplitude coefficients, and thus the polarization of the light, are substantially unchanged for angle of incidence 326 (and, by symmetry, for angle of reflection 328) substantially less than 30 degrees from the normal 306 to the surface 304. The result that the polarization is substantially unchanged for angle incidence 326 (angle of reflection 328) negligible with respect to the normal 306 to the surface 304 is unchanged for values of the index of refraction in region 302 substantially the same as that used in the calculation shown in Fig. 9.

Referring back to Fig. 1, the first planar mirror 116 is positioned relative to a first off-axis parabolic mirror 126 such that the broadband beam of light 114 is collimated on reflection from the first off-axis parabolic mirror 126. A

suitable off-axis parabolic mirror can be custom manufactured by Edmond Industrial Optics using diamond turning. A commercially available example of such an off-axis parabolic mirror is model H47-085 from Edmond Industrial Optics. Referring to Fig. 4, the 5 broadband beam of light **114** has a maximum angle of incidence **130** and a maximum angle of reflection **132** relative to a normal **128** to the off-axis parabolic mirror **126**. By keeping the maximum angle of incidence **130** and the maximum angle of reflection **132** small, that is, negligible with respect to the normal **128**, 10 changes to the polarization of the broadband beam of light **114** are minimized. The same technique is used for off-axis parabolic mirrors **140, 162, 168, 188** and **194** in the apparatus.

Referring back to Fig. 1, the broadband beam of light **114** is redirected on reflection off of a second planar mirror **138**. 15 The broadband beam of light **114** incident and reflected off of the second planar mirror **138** is collimated. The second planar mirror **138** is positioned relative to a second off-axis parabolic mirror **140** such that the broadband beam of light **114** illuminates and is brought into focus on a sample **144**.

Referring to Fig. 5, the broadband beam of light **114** is 20 collimated when incident on the second off-axis parabolic mirror **140**. This ensures that the broadband beam of light **114** will come to focus at a distance **142** from the second off-axis parabolic mirror **140**. There is a known relationship between the 25 distance **142** and focal length along axis of the second off-axis parabolic mirror **140**. A person of skill in the art will be able to determine the focal length from the curvature of the second off-axis parabolic mirror **140**. By adjusting the position of the second off-axis parabolic mirror **140** relative to the sample **144**,

the broadband beam of light **114** is brought into focus on a top surface **146** of the sample **144**. It is important, however, that the position of the second planar mirror **138** be adjusted such that the second planar mirror **138** maintains the same position  
5 relative to the second off-axis parabolic mirror **140**. In this way, the collimated light reflected off of the second planar mirror **138** remains parallel to the axis (not shown) of the second off-axis parabolic mirror **140**. Since the broadband beam of light **114** incident on the second planar mirror **138** is collimated, this adjustment of the position of the second planar mirror **138** and the second off-axis parabolic mirror **140** does not necessitate adjustment of the position of the other components  
10 in the first optical light path **110**.

Referring to Fig. 6, the broadband beam of light **114** has a cross-section **210** with a diameter **220** defined as twice the distance from the center of the cross-section **210** where the light intensity is reduced by a factor of  $1/e$ . The broadband beam of light **114** has a diameter **220** greater than 500 microns at the light source **112** and a diameter **220** between 50 microns and  
20 80 microns on the top surface **146** of the sample **144**. This reduction is proportional to the ratio of the focal lengths of off-axis parabolic mirror **140** and off-axis parabolic mirror **126**.

Referring back to Fig. 5, the small diameter **220** of the broadband beam of light **114** illuminated on the top surface **146** of the sample **144** corresponds to a small spread of angles in the cone of rays in the broadband beam of light **114** incident on the sample **144**. The broadband beam of light **114** incident on the top surface **146** of the sample **144** has a minimum angle of incidence **152** and a maximum angle of incidence **154** relative to a normal  
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150 to the top surface 146 of the sample 144. By keeping the maximum angle of incidence 154 small, that is, negligible with respect to the normal 150, changes to the polarization of the broadband beam of light 114 are minimized.

5 Referring back to Fig. 1, the broadband beam of light 161 is reflected from the top surface 146 of the sample 144 (broadband beam 161 is identified by its extremal rays in Fig. 1). The broadband beam of light 161 is redirected and magnified in the second optical light path 160. The broadband beam of 10 light 161 is redirected on reflection off of a first off-axis parabolic mirror 162 and then redirected on reflection off of a first planar mirror 164. In a manner similar to that used in adjusting the position of second planar mirror 138 and second off-axis parabolic mirror 140 in the first optical light path 110, the position of the first off-axis parabolic mirror 162 and 15 the first planar mirror 164 relative to the top surface 146 of the sample 144 are adjusted such that the broadband beam of light 161 incident and reflected from the first planar mirror 164 is collimated. This ensures that the adjustment of the position of the first off-axis parabolic mirror 162 and the adjustment of the position of the first planar mirror 164 does 20 not necessitate adjustment of the position of other components in the second optical light path 160. Referring back to Fig. 5, the small diameter 220 of the broadband beam of light 114 on the 25 top surface 146 of the sample 144 corresponds to a small spread of angles in the cone of rays in the broadband beam 161 of light with a minimum angle of reflection 156 and a maximum angle of reflection 158. By keeping the maximum angle of reflection 158 small, that is, negligible with respect to the normal 150,

changes to the polarization of the broadband beam of light **161** are minimized.

Referring back to Fig. 1, the broadband beam of light **161** is redirected on reflection off of a second off-axis parabolic mirror **168**. The broadband beam of light **161** is redirected on reflection off of the second planar mirror **170** and illuminates a first detector **172**. The entrance aperture **171** of the first detector **172** is positioned at the focal length of the second off-axis parabolic mirror **168**. A person of skill in the art will be able to determine the focal length from the curvature of the second off-axis parabolic mirror **168**.

Referring back to Fig. 5, after transmission through the sample **144** the broadband beam of light **181** exits the sample through a bottom surface **148** of the sample **144** (broadband beam **181** is identified by its extremal rays in Fig. 5). The cone of rays in the broadband beam of light **181** transmitted through the sample **144** has minimum angle of transmission **184** and maximum angle of transmission **186** relative to a normal **182** to the bottom surface **148** of the sample **144**. By keeping the maximum angle of transmission **186** small, that is, negligible with respect to the normal **182**, changes to the polarization of the broadband beam of light **181** are minimized. Referring back to Fig. 1, the broadband beam of light **181** is redirected and magnified by the third optical light path **180**. The broadband beam of light **181** is redirected on reflection off of a first off-axis parabolic mirror **188** and then redirected on reflection off of a first planar mirror **190**. In a manner similar to that used in adjusting the position of second planar mirror **138** and second off-axis parabolic mirror **140** in the first optical light path

110, the position of the first off-axis parabolic mirror 188 and the first planar mirror 190 relative to the top surface 146 of the sample 144 are adjusted such that the broadband beam of light 181 incident and reflected from the first planar mirror 190 is collimated. This ensures that the adjustment of the position of the first off-axis parabolic mirror 188 and the adjustment of the position of the first planar mirror 190 does not necessitate adjustment of the position of other components in the third optical light path 180. Since the broadband beam of light 114, 161 and 181 is collimated substantially perpendicular to the sample 144 over a portion of the first optical light path 110, the second optical light path 160 and the third optical light path 180, in an embodiment of this invention the adjustment of the second planar mirror 138 and second off-axis parabolic mirror 140, the first off-axis parabolic mirror 162 and the first planar mirror 164, and the first off-axis parabolic mirror 188 and the first planar mirror 190 relative to the top surface 146 of the sample 144 is accomplished with a group of mechanically coupled elements. The broadband beam of light 181 is redirected on reflection off of a second off-axis parabolic mirror 194. The broadband beam of light 181 is redirected on reflection off of the second planar mirror 196 and illuminates a second detector 198. The entrance aperture 197 of the second detector 198 is positioned at the focal length of the second off-axis parabolic mirror 194. A person of skill in the art will be able to determine the focal length from the curvature of the second off-axis parabolic mirror 194.

Fig. 3 illustrates a side view of the first planar mirror 116 in the first optical light path 110. In a preferred embodiment of the invention, the planar mirror 116 includes a UV-enhancing aluminum coating 124. As an example, the model 01-5 MGF-005/028 planar mirror from Melles-Griot has a UV-enhancing aluminum coating 124. In a preferred embodiment, such UV-enhancing aluminum coatings are used on the other planar mirrors 138, 164, 170, 190 and 196 in the first optical light path 110, the second optical light path 160 and the third optical light 10 path 180.

Fig. 4 illustrates a side view of the first off-axis parabolic mirror 126 in the first optical light path 110. In a preferred embodiment of the invention, the off-axis parabolic mirror 126 includes a UV-enhancing aluminum coating 134. Edmond 15 Industrial Optics is a supplier of such UV-enhanced aluminum coatings. In a preferred embodiment, such UV-enhancing aluminum coatings are used on the other off-axis parabolic mirrors 140, 162, 168, 188 and 194 in the first optical light path 110, the second optical light path 160 and the third optical light path 20 180.

Fig. 2 illustrates alternate embodiments of the invention. The first optical light path 110 includes a polarizing means 136 for polarizing the broadband beam of light 114 in one of two orthogonal directions. A suitable device is a model PTH-SMP 25 Glan Thompson-type calcite polarizer made by Harrick. The second optical light path 160 includes a polarizing means 166, such as a polarizing analyzer. Once again, the model PTH-SMP Glan Thompson-type calcite polarizer made by Harrick is

suitable. The third optical light path **180** includes a polarizing means **192**, such as a polarizing analyzer.

In another embodiment of this invention, the third optical light path **180** also includes an optical fiber **199** for redirecting the broadband beam **181** from the third optical light path **180** to the second detector **198**.

In another embodiment of this invention, the broadband beam **181** from the third optical light path **180** is redirected and illuminated onto the first detector **172** eliminating the need for the second detector **198**. Additional optical components, such as a beam splitter, may be added as is known in the art to ensure that broadband beam **161** and broadband beam **181** are coaxial when they illuminate the first detector **172**. A chopper may also be added.

Referring back to Fig. 1, the first detector **172** and the second detector **198** depend on the type of optical characterization to be performed on the sample **144**. For measurements of reflected or transmitted intensity as a function of wavelength, the first detector **172** and the second detector **198** with a monochromator, a diode array or a photomultiplier tube is suitable. A monochromator with a 512-element diode array (Model PDA-512) is available from Control Development. A mechanically scanned monochromator is known in the art. A suitable photomultiplier is model R928 from Hamamatsu. For a spectroscopic ellipsometer, a polarization analyzer, such as the model PTH-SMP Glan Thompson-type calcite polarizer made by Harrick, in addition to the monochromator, the diode array or the photomultiplier tube is suitable. In one embodiment, the polarization analyzer can be incorporated in the first detector

172 and the second detector 198. The analysis techniques in United States patent US 4,905,170 to Forouhi et al. and United States patent application US 10/607,410 to Li et al., hereby incorporated by reference, can be used to determine optical 5 characteristics of the sample 144 from the measurements.

By employing substantially reflective optical components and off-axis parabolic mirrors with collimated incident broadband beam of light 114, reflected broadband beam of light 161, and transmitted broadband beam of light 181, the invention 10 minimizes chromatic aberration in the first light path 110, the second light path 160 and the third light path 180. This enables the small diameter 220 of the broadband beam of light 114 and 161 on the top surface 146 of the sample 144 as well as 15 optical characterization of reflection and transmission properties using the single light source 112. The diameter 220 of the broadband beam of light 114 and 161 is small enough to resolve spatial variations in optical characteristics on the top surface 146 of the sample 144 yet large enough to spatially average the optical characteristics of the sample 144. 20 Artifacts associated with diamond-turned parabolic mirrors are not a concern in this invention since the diameter 220 of the broadband beam of light 114 and 161 on the top surface 146 and the diameter 220 of the broadband beam of light 181 on the bottom surface 148 of the sample 144 are not diffraction 25 limited. The principle impact of such artifacts is scattering of the broadband beam of light 114, 161 and 181, which is not a concern in this invention since these scattered rays will not be illuminated onto the first detector 172 or the second detector 198.

Furthermore, by ensuring that the maximum angle of incidence 120 and reflection 122 for the planar mirrors 116, 138, 164, 170, 190 and 196 are small, that is, negligible with respect to the normal 118, that the maximum angle of incidence 130 and reflection 132 for the off-axis parabolic mirrors 126, 140, 162, 168, 188 and 194 are small, that is, negligible with respect to the normal 128, that the maximum angle of incidence 154 and the maximum angle of reflection 158 from the top surface 146 are small, that is, negligible with respect to the normal 150, and that the maximum angle of transmission 186 is small, that is, negligible with respect to the normal 182 to the bottom surface 148 changes to the polarization of the broadband beam of light 114, 161 and 181 are minimized.

The first, second and third optical light paths 110, 160 and 180 in this invention have been described with parabolic mirrors 126, 140, 162, 168, 188 and 194. One skilled in the art will recognize that other mirror shapes such as a toroidal mirror as well as those based on conic sections, such as elliptical, hyperbolic and spherical, are also suitable. In addition, another reflective surface may be substituted for the planar mirrors 116, 138, 164, 170, 190 and 196.

In view of the above, it will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.